Stellar Burning and Mixing

*Falk Herwig, Alexander Heger, and Frank Timmes (T-6); and Rob Hueckstaedt and Rob Coker (X-2); **fherwig@lanl.gov***

During most phases of stellar evolution, nuclear burning and convective mixing operate on largely different time scales. However, 1D astrophysical modeling of stars has been able over the past years to tie several important observational peculiarities in stars to rapid nuclear burning in convective regions in which mixing and nuclear energy release proceeds on comparable time scales.

We have identified one type of object—the born-again giants—that provide astrophysical observables in the form of light curves and elemental surface abundances that are especially well suited to test how nuclear burning may affect the inherently multidimensional mixing process of convection [1]. In these objects, a thermonuclear runaway of the helium shell on top of an electron-degenerate core (a young White Dwarf) causes a rapid expansion of the outer layers, and the star evolves back to high luminosity and low surface temperature—an evolutionary state from which it just descended (Fig. 1).

Using 1D calculations we find a link between the turbulent diffusion coefficient in the He-shell flash driven by the convection zone and the observable time scale of the change of stellar parameters (Fig. 2). In these astrophysical objects, mixing may be less efficient because convection brings hydrogen into the very hot carbon-rich helium-burning layer. This is a very volatile mixture that burns on the convective time scale, adding buoyancy to blobs in which hydrogen and carbon were mixed together.

An outstanding scientific puzzle concerns the mechanisms by which the first significant amounts of nitrogen were produced in the universe. Processes similar to those given above may play a role in the helium burning and nitrogen production of the first generation of stars. In these stars, a convective helium-burning carbon-rich region comes into contact with a hydrogen-rich layer. Also here, a convective helium-burning carbon-rich region gets in contact with a hydrogen-rich layer. The key questions are (1) how much mixing occurs before rising entropy gradients due to burning eventually shuts off further mixing, (2) how much nitrogen is being produced, and (3) how many protons are mixed into the center of the star. The degree of proton mixing has implications for the production of neutron-rich elements.

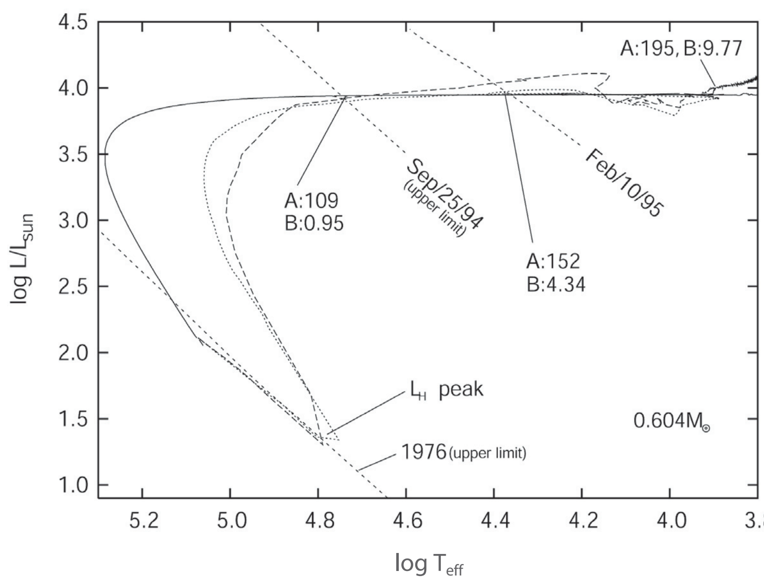

***Figure 1—** A thermonuclear runaway of the helium shell on top of an electron-degenerate core (a young White Dwarf) causes a rapid expansion of the outer stellar layers, which leads the star back to high luminosity and low surface temperature—an evolutionary state from which it just descended.*

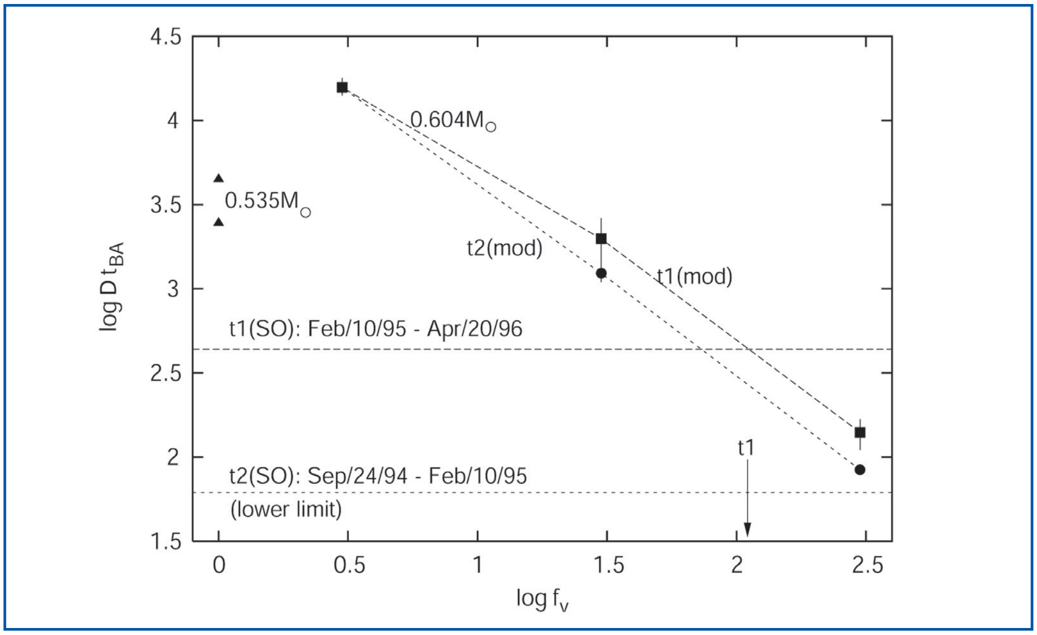

Figure 2—
A link between the mixing velocity in the He-shell flash driven convection zone and the observable time scale of the change of stellar parameters. This case implies that nuclear burning may reduce mixing by a factor ~100.

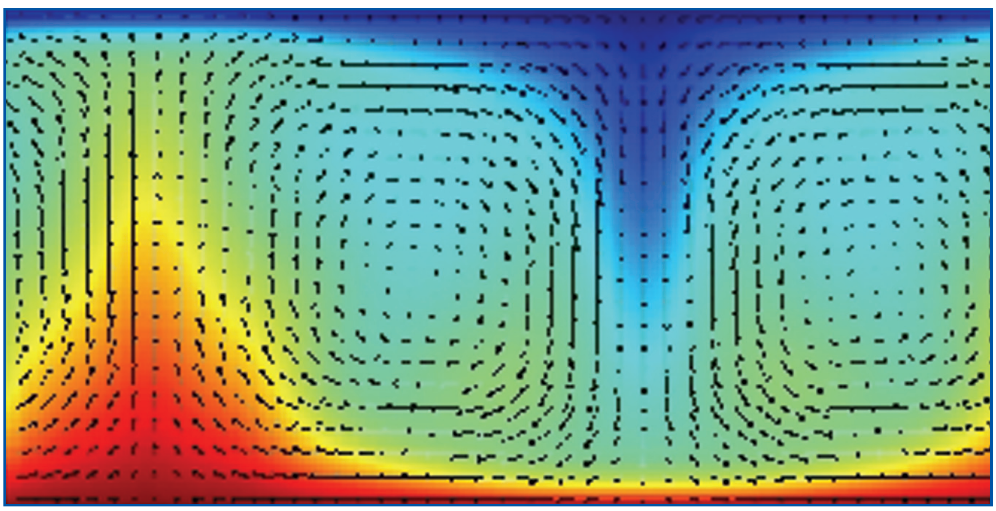

Figure 3—
Snapshot of temperature of 2D simulation box for Rayleigh-Bernard-like test problem with RAGE.

We have started a project using RAGE and FLASH to model the effect of rapid nuclear energy release on turbulent flow patterns in convection. We are currently setting up Rayleigh-Bernard-like test problems of convection (Fig. 3) to serve as a starting point for developing simulations that represent stellar conditions. We will include a stellar equation of state as well as thermonuclear burning (TN burn) into RAGE. By comparing simulations with and without TN burn we aim to recover the averaged effect of burning on the mixing suggested by astrophysical observables.

This project takes RAGE into a new application regime. Complementary 1D astrophysical modeling allows us to access specific observables from the astrophysical context to probe the RAGE behavior with regard to burning and mixing. This verification problem is innovative because it utilizes a certain class of astrophysical observational data for the first time.

[1] F. Herwig, "The Evolutionary Timescale of Sakurai's Object: A Test of Convection Theory?" *ApJ Lett.* **554**, 74 (2001).

𝒯